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13. ABSTRACT (Maximum 200 words)

Results obtained from our studies on the toughening mechanism, quantitative fractography and dynamic fracture of ceramics and ceramic matrix composites are summarized in this final report. One of the most significant accomplishments was to quantify, for the first time, the energy dissipation rate in the brittle SiC_W/Al_2O_3 ceramic matrix composite (CMC) using moire interferometry together with finite element analysis. The same hybrid experimental-numerical analysis was also used to determine the resistance curve, which compared favorably with the theoretically predicted toughening effect, in TiB_2. A procedure for estimating the percentage areas of transgranular fracture in ceramics and CMC using line scanning profiles of scanning electron microscopy was developed. Larger percentage areas, which were determined by this procedure of transgranular fractures in Al_2O_3 and SiC_W/Al_2O_3, were related to rapid crack propagation thus suggesting a micromechanism which reduces the dynamic crack arrest capability of brittle materials. A unique bar impact test was developed for "clean" dynamic fracture testing of ceramics and CMC's and was used to characterize the dynamic fracture responses of Al_2O_3 and SiC_W/Al_2O_3.

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FINAL REPORT

DYNAMIC BEHAVIOR OF CERAMIC COMPOSITES

by

A.S. Kobayashi and M. Taya

October 1991

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Department of Mechanical Engineering

College of Engineering

University of Washington

1. Precis of Significant Accomplishments

The objective of this research program was to characterize the dynamic behavior of ceramic composites. The specific objectives under the original contract entitled "Static and Dynamic Mechanical Behavior of Ceramic Composites" for the period of February 1, 1987 through January 31, 1989 were to:

i. Study the static and dynamic fracture behavior of ceramic matrix composites (CMCs).

ii. Study the plate impact resistance of CMCs and its residual mechanical properties.

The above contract objectives were modified in a renewal contract entitled "The Mechanical Behavior of Ceramic Composites under Dynamic and Thermal Loadings" for the period of February 1, 1989 through October 31, 1991 to:

i. Study the tensile behavior of ceramic matrix composites (CMC) at different strain rates and temperature up to 1400°C.

ii. Study the dynamic fracture process of CMC's subjected to impact loading.

iii. Determine the micromechanics, which resulted in the findings of i. and ii. of the above and then identify the microstructure characteristics which will yield higher mechanical properties at high strain rate loadings.

Toughening Mechanism

In the static characterization study of the fracture behavior of CMC's, a hybrid experimental-numerical method was used to determine the crack growth resistance, K_R, versus crack extension, Δa, relation for TiB_2-particulate/SiC-matrix (TiB_2/SiC) composite. The hybrid experimental-numerical method involved finite element method (FEM) analysis and moire interferometry for analyzing chevron-notch, wedge-loaded, double cantilever-beam (CN-WL-DCB) specimens. This CN-WL-DCB specimen provided a well-developed fracture process zone associated with steady state crack growth in an otherwise brittle specimen. By using the hybrid experimental-numerical method, crack growth resistance, K_R, versus crack extension, Δa, curves of the SiC matrix only and the TiB_2/SiC composite were obtained where the crack growth resistance of the composite increased with crack extension while that of the unreinforced matrix remained constant. The mechanism for increased K_R of the composite was attributed to the TiB_2 particulates which had presumably diverted the crack and thereby increased the resistance to the crack opening.

Moire interferometry was also used interactively with a three-dimensional finite element model of the specimen to determine the crack closure stress (CCS) versus crack opening displacement (COD) relation in the fracture process zone (FPZ) of SiC_w/Al_2O_3 chevron-notched, double cantilever beam (DCB) specimen. The variations in energy release rate and the energy dissipation rate with intermittent stable crack extension were computed from the stress intensity factors and the work done by the CCS acting on the COD in a FPZ, respectively. The discrepancy at the initial phase of crack extension was attributed to the coarse finite element mesh and the effect of the double singularities where the crack front intersected with the two sides of the chevron notch. Otherwise, the energy dissipated at the FPZ coincided with the energy released by crack extension during the last two increments of crack extension. These results suggest that the CCS versus COD relation represented the dominant toughening mechanism in this brittle SiC_w/Al_2O_3-matrix composite.

Quantitative Fractography

Previous fractography analysis of Al_2O_3 three point bend specimens fractured under static and impact loadings showed that rapid crack propagation is always accompanied by transgranular fracture regardless of the magnitude of the driving force, i.e., the dynamic stress intensity factor (SIF), and the crack velocity. The percentage areas of transgranular fracture decreased from an average of 16% during the initiation phase of rapid crack propagation to an average of 10% at slower crack propagation in an impacted Al_2O_3 three-point bend specimen. For the statically loaded specimen, the percentage of transgranular areas decreased from 5 to 2%. The higher percentage areas of transgranular fracture during the initiation phase was attributed to the higher crack velocity and the higher dynamic SIF due to the overdriving force generated by the blunt crack tip.

The above results indicated that the lack of dynamic crack arrest in ceramics and in some class of CMC is due to the transgranular fracture mode which dominates rapid crack propagation. This hypothesis deserves further investigation and thus a procedure was developed to quantify the immense data on percentage area of transgranular fracture by relating it to the fracture profile. The fracture profile in turn was related to the line scanning profile (LSP) of scanning electron microscopy. A PC based software, which processes the scanned data and output the roughness spectrum and percentage area of transgranular fracture, was completed. The fracture surfaces of SiC_w/Al_2O_3 chevron notched DCB specimens were analyzed using this procedure. The percentage areas of transgranular failures determined by this procedure were 58% for rapid crack propagation and 42-43% for stable crack growth. The micro-mechanics which governs transgranular versus intergranular failures, however, remains to be identified.

DYNAMIC FRACTURE OF CMC

This phase of the contract consisted of two projects of impact damage assessment by split Hopkinson bar tests and by drop-weight testing.

Impact testing of SiC_w/Al_2O_3 single-edge-notched bend specimens subjected to drop weight loading at room temperature and 1000°C was a continuation of a former NASA research with an upgraded LIDG system and precracked SiC_w/Al_2O_3 three point bend specimens. Precracking was done by the single-edge-precracked beam (SEPB) method. The impact data showed that a dynamic crack arrest stress intensity factor did not exist in the Al_2O_3, Si_3N_4 and SiC_w/Al_2O_3 specimens and was consistent with previous findings. While the percentage area of transgranular failure increased almost linearly with the crack velocity, a large percentage area of transgranular fracture persisted at a low crack velocity. The kinematic constraint of a rapidly propagating crack most likely enforced transgranular fracture during crack deceleration thus resulting in continuing crack extension under a dynamic stress intensity factor substantially lower than the static fracture toughness.

Rectangular bars of Al_2O_3 and 29% volume fraction SiC_w/Al_2O_3 composite with sharp precracks were tested with a newly developed bar impact facility and a new data reduction procedure. The fracture surface morphology was studied and compared with the impact velocity and the dynamic stress intensity factor, K_I^{dyn}, history. The crack propagation history and K_I^{dyn} curves for the Al_2O_3 and 29% volume fraction SiC_w/Al_2O_3 composite composite were virtually the same indicating that the short SiC whiskers were ineffective under dynamic fracture. SEM study revealed five distinct fracture morphology regions with increased percentage area of transgranular fracture in the ceramic matrix of both the Al_2O_3 and SiC_w/Al_2O_3 with rapid crack propagation. Also the high dynamic stress intensity factor caused multiple microscopic crack planes to form and then join as the crack advanced.

2. ONR Technical Reports and Other Related Publications

The following eight ONR Technical Reports and fourteen papers were published under this ONR contract.

Technical Reports

"Spall Resistance of Alumina," L.R. Deobald, M. Taya, A.S. Kobayashi and H.S. Yoon, ONR Technical Report No. UWA/DME/TR-89/1.

"Toughening of a Particulate-Reinforced/Ceramic-Matrix Composite," M. Taya, S. Hayashi, A.S. Kobayashi and H.S. Yoon, ONR Technical Report No. UWA/DME/TR-89/2.

"A SEM Procedure for Quantifying Transgranular Fracture in Brittle Material," W.-J. Yang, C.-T. Yu and A.S. Kobayashi, ONR Technical Report No. UWA/DME/TR-90/3.

"Fracture Process Zone in a Ceramic Composite," C.-T. Yu and A.S. Kobayashi, ONR Technical Report No. UWA/DME/TR-91/4.

"Dynamic Fracture Response of Al_2O_3, Si_3N_4 and SiC_w/Al_2O_3," Y. Takagi and A.S. Kobayashi, ONR Technical Report No. UWA/DME/TR-91/5.

"A Bar Impact Tester for Dynamic Fracture Testing of Ceramic and Ceramic Composites," L.R. Deobald and A. S. Kobayashi, ONR Technical Report No. UWA/DME/TR-91/6.

"Dynamic Fracture Characterization of Al_2O_3 and SiC_w/Al_2O_3," L.R. Deobald and A.S. Kobayashi, ONR Technical Report No.UWA/DEM/TR-91/7.

"A Bar Impact Tester and Data Reduction Procedure for Dynamic Fracture Testing," L.R. Deobald and A.S. Kobayashi, ONR Technical Report No. UWA/DME/TR-98/8. (To be distributed in November 1991.)

Conference Proceedings

"Crack Growth Resistance of TiB_2 Particulate/SiC Matrix Composite," S. Hayashi, L. Deobald, M. Taya, and A.S. Kobayashi, Mechanics of Composite Materials, 1988, ed. by G.J. Dvorak and N.W. Laws, ASME AMD-Vol. 92, pp. 217-223, 1988.

"Thermal Cycling Damage of Ceramic Matrix Composite," W.D. Armstrong and M. Taya, Proc. 4th Japan Conference.on Composite Materials, Technomic Publishing Company, pp. 765-775,1989.

"Modeling of Physical Properties of Metallic and Ceramic Composites: Generalized Eshelby's Model," Proc. 9th Riso Intl. Symp. on Metall. and Mater. Sci.: Mechanical and Physical Behavior of Metallic and Ceramic Composites, eds. S.I. Andersen, H. Lilholt and O.B. Pedersen, Riso National Laboratory, Denmark, 1988, pp. 201-231.

"Plate Impact Resistance of Ceramic Materials," L.R. Deobald, M. Taya, A.S. Kobayashi, and H.S. Yoon, H.S., Proceedings of 1989 SEM Spring Conference on Experimental Mechanics, Society of Experimental Mechanics, pp. 122-129, 1989.

"Further Studies on Dynamic Fracture Responses of Alumina and SiC_w/Al_2O_3 Composite," Y. Takagi and A.S. Kobayashi, Proc. of Symposium on Elevated Temperature Crack Growth, eds. S. Mall and T. Nicholas, ASME MD-Vol. 18, pp. 145-148, 1990.

"Dynamic Fracture of Al_2O_3 and SiC_w/Al_2O_3 Composite," Y. Takagi and A.S. Kobayashi, *Fracture Mechanics of Ceramics,* eds. M. Sakai, R.C. Bradt, D.P.H. Hasselman, and D. Muntz, Plenum Publ., 1992.

"Fracture Process Zone in Ceramics and Ceramic Composites," C.-T. Yu and A.S. Kobayashi, Mechanical Behavior of Materials-IV, ed. M. Jono and T. Inoue, Pergamon Press, pp. 423-428, 1991.

"Dynamic Fracture Resistance of Al_2O_3 and SiC_w/Al_2O_3," L.R. Deobald and A.S. Kobayashi, Journal de Physique IV, Colloque C3, suppl. au Journal de Physique IV, vol. 1, October 1991, C3-727-C-732.

"Fracture Process Zone of a Ceramic Composite, An Experimental Analysis," C.T. Yu and A.S. Kobayashi, ASME 1991, WAM Preprint.

"Impact Testing of Al_2O_3 and SiC_w/Al_2O_3," L. R. Deobald and A.S. Kobayashi, to be submitted to IRC 92 Materials for High Performance, Birmingham,UK, September 7-10, 1992.

Refereed Papers

"Toughening of a Particulate-Reinforced/Ceramic-Matrix Composite by Thermal Residual Stress," M. Taya, S. Hayashi, A.S. Kobayashi and H.S. Yoon, Journal of American Ceramics Society, Vol. 73, No. 5, pp. 1382-1391, May 1990.

"SEM Quantification of Transgranular vs. Intergranular Fracture," W.-J. Yang, C-T. Yu and A.S. Kobayashi, Journal of American Ceramic Society, Vol. 74, No. 2, pp. 290-295, Feb. 1991.

"Dynamic Fracture Characterization of Al_2O_3 and SiC_w/Al_2O_3," L. R. Deobald and A.S. Kobayashi, submitted to the Journal of American Ceramic Society.

"A Bar Impact Tester and Data Reduction Procedure for Dynamic Fracture Testing," L.R. Deobald and A.S. Kobayashi, submitted to Fracture Mechanics, 24th Symposium, ASTM.

3. ACKNOWLEDGEMENTS

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